



Fermi National Accelerator Laboratory

FERMILAB-Pub-88/118-A
August 1988

On Relative Supernova Rates and Nucleosynthesis Roles

W. David Arnett^{1,2}, David N. Schramm¹

and

James W. Truran³

ABSTRACT

It is shown that the ^{56}Ni - ^{56}Fe observed in SN 1987A argues that core collapse supernovae may be responsible for more than 50% of the iron in the galaxy. Furthermore it is argued that the time averaged rate of thermonuclear driven Type I supernovae may be at least an order of magnitude lower than the average rate of core collapse supernovae. The present low rate of Type II supernovae (below their time averaged rate of $\sim 1/10$ yr) is either because the past rate was much higher or because many core collapse supernovae are dim like SN 1987A. However, even in this latter case they are only an order of magnitude dimmer than normal Type II's, due to the contribution of ^{56}Ni decay to the light curve.

¹ The University of Chicago and Fermilab.

² The University of Arizona.

³ The University of Illinois.



INTRODUCTION

Recent observational and theoretical developments with respect to supernovae have provided interesting and important constraints on the contributions of supernovae of Types I and II to galactic nucleosynthesis. In particular, theoretical modelling of the light curves of Type I supernovae has led to the conclusion that approximately $0.7 M_{\odot}$ must be ejected in the form of $^{56}\text{Fe}(^{56}\text{Ni})$ (Arnett 1988; Woosley 1988). More recently, observations of supernovae 1987A indicate an exponentially falling light curve with a lifetime compatible with ^{56}Co decay; the observed luminosity and the distance dictate that approximately $0.07 M_{\odot}$ of matter was ejected in the form of nuclei of mass $A=56$ in this Type II supernova event. We have available, for the first time, a measure of the relative contributions of supernovae of Types I and II to the abundance of ^{56}Fe in galactic matter. We briefly explore some interesting possible constraints these mass estimates permit us to impose on galactic chemical evolution and on the rates of supernova activity over the histories of our Galaxy and other galaxies.

DEFINITIONS

To avoid many of the misconceptions that persist in supernova, rate discussions, it is imperative that we define terms. In particular, we want to isolate the internal physics of an event from the traditional astronomical classification based on the character of the external optical outburst.

The optical outbursts have traditionally been split into two major categories. Type I (no hydrogen, $L \sim 10^9 L_\odot$, $V_{\text{rms}} \sim 10^4$ km/sec) and Type II (hydrogen, $10^8 L_\odot$, $V_{\text{rms}} \sim 5000$ km/sec).

Physically, Type II's are associated with young massive ($M > 10 M_\odot$) stars undergoing core collapse. Standard Type I's are associated with the thermonuclear detonation or deflagration of a C/O white dwarf. Rather than get into the inelegant details of traditional classification schemes (Type IB's, etc.,) we will classify supernova in this paper by the physics, namely

1. Thermonuclear explosion
2. Core collapse

The surface "weather", composition and exterior structure which determine how a traditional astronomer classifies supernovae will be ignored, except when discussing observational predictions.

Note that from the physics point of view, a core collapse model produces a dense remnant (either a neutron star or a black hole) and ejects large amounts of the heavy elements from oxygen to iron. However, the Fe ejecta comes from near the $\sim 1.4 M_\odot$ core where all massive stars have similar structures, while the oxygen and other intermediate elements come from the mantle where the mass of each region varies with the mass of the star. Therefore the O/Fe ratio will vary with the mass of the star. As mentioned above, from SN 1987A we know that about $0.07 M_\odot$ of Fe gets ejected. This amount should hold approximately for all core collapse models. The mass of ejected oxygen goes from perhaps $\sim 0.1 M_\odot$ for the extreme

low end of the mass range to $\sim 10 M_{\odot}$ for the most massive core collapse events.

Core collapse is the prime nucleosynthetic event; thermonuclear explosions skip the bulk of the intermediate mass nuclei on their way to creating iron. It is now widely believed that this almost complete conversion of burned fuel to Fe is what powers traditional Type I light curves, with their long decay time. Such powering necessarily demands that $>60\%$ of the core is converted to iron.

INTEGRAL RATE OF CORE COLLAPSES IN THE GALAXY

Since the bulk of the heavy elements are ejected in core collapse events, the "average" rate of nucleosynthesis in the Galaxy gives us a good estimate of the average rate of core collapse events.

Taking the mass of the disk of our Galaxy as $10^{11} M_{\odot}$ and its age as 10^{10} yr and the mass fraction of oxygen in the disk as $\sim 8.5 \times 10^{-3}$, one estimates the total mass of oxygen in the disk as $\sim 8.5 \times 10^8 M_{\odot}$. The oxygen yields of massive stars increase sharply with the mass of the star. Detailed yield estimates have been carried out in a continuous series of calculations by Arnett and Weaver and Woosley and their collaborators (c.f. Thielemann & Arnett 1985 and Woosley & Weaver, 1982 as well as Arnett 1988 and Woosley 1988). Although some difference exist from year-to-year and between the two groups the numbers we will use in our arguments are

a reasonable representation of the results and their spread. A steeply falling initial mass function of the Salpeter type would argue that the typical core collapse supernova is one with a mass near the lower mass cutoff (c.f. Arnett & Schramm 1973). Such an object ejects $\sim 0.5 M_{\odot}$ oxygen. The mass averaged yield using a Salpeter mass function is slightly higher due to the higher oxygen yields of the more massive stars. The actual value is sensitive to the high mass cutoff on the mass function and to mass loss assumptions. For reasonable choices, the mass averaged yield ranges from 0.7 to 1.5 M_{\odot} of oxygen. For the steeper Scalo mass function the averaged yields are correspondingly lower and can almost approach the yield of the "typical" supernova selected by number. To within the uncertainties, it seems that to produce $\sim 10^9 M_{\odot}$ of oxygen would require about 10^9 supernovae. Since these occurred over the 10^{10} yr galactic lifetime, this implies an average core collapse supernova rate of $\sim 1/10$ yr over the history of the Galaxy.

Although there is about a factor of 2 uncertainty in this average rate, it seems clear that the average is higher than the currently observed visible Type II supernova rate from external Sb and Sc galaxies which is $\sim 1/50$ yr (c.f. Trimble 1988, Vandenberg 1988, McClure & Evans 1987) also to a factor of ~ 2 accuracy.

The reason for this difference may be either that the past rate was much higher or that the observed Type II rate does not include a large fraction of the actual core collapse events. This latter possibility would occur if many core collapse events were no more

luminous than SN 1987A or if they were embedded in dense obscuring regions, such as is the case for CasA.

Alternative approaches to finding supernova rates, such as remnant statistics, pulsar statistics or X-ray heating of the disk are plagued by model dependencies on lifetimes, beaming factors, hot X-ray chimneys, etc. and may be less reliable than the nucleosynthesis arguments.

Galactic evolution models can accommodate a present rate either equal to or below the average rate as long as the average is maintained overall. For example, constant rate models can utilize infall, outflow or variable initial mass function to fit abundance versus age data (c.f. Tinsley 1976) while high early rate models have the star formation rate decrease with time to fit the data. Standard one-zone galactic evolution, models in the absence of infall or X-ray outflow with a constant IMF, do predict such decreasing rates as the available gas is used up. However, it should be remembered that a comparison of nucleosynthetic rates averaged over nuclearchronometers of different lifetimes argues that rates have not changed by more than a factor of ~ 2 (Meyer and Schramm 1986).

For the future it is clear that supernova searches need to be refined so that low luminosity events such as SN 1987A can be seen in external galaxies. Note that because of the $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ decay, SN 1987A eventually reached a peak luminosity that was within an order of magnitude of a "normal" Type II, so with appropriate

search techniques even such faint ones might be able to be observed in more distant galaxies. Of course, observations will be more difficult in high luminosity galaxies than in low luminosity dwarfs so care must be taken to avoid biases.

This minimal luminosity from SN 1987A shows us that even with a blue envelope structure, the resulting collapse event yields an appreciable luminosity. Therefore, searches sensitive to one order of magnitude fainter should be successful regardless of whether or not the progenitor is red or blue, unless the object is embedded in a dense cloud. In any case, this avoids the complication as to whether or not red or blue progenitors are more or less likely in galactic disks.

Fe YIELDS

Notice that, with an average core collapse rate of 1/10 yr and the assumption that all core collapses produce $0.07M_{\odot}$ of Fe as did SN 1987A, core collapse events alone can produce about $10^8 M_{\odot}$ of Fe. This is sufficient to explain half the Galactic Fe abundance. Therefore, within the uncertainties, thermonuclear event iron production may even be unnecessary to the Galactic iron production. Most likely it is only comparable to the yields from core collapse events. Since thermonuclear Type I's produce $0.7M_{\odot}$ of Fe this argues that the average Galactic rate of such events must be no more than their present extragalactic observed rate of 1/70 yr (factor of 2 accuracy) (c.f. Vandenberg, McClure and Evans 1987)) or they

would over produce Fe. In other words, the rate of thermonuclear events (Type I's) must either be constant or decrease as one looks into the past (high red shift) whereas the rate of core collapse events must either be much, much higher in the past than the present observed Type II rate or the present collapse rate itself is about a factor of 5 higher than the observed Type II rate. In either case high redshift studies should find at least an order of magnitude more collapse events than thermonuclear events.

Obviously an important check on these arguments is to verify that other core collapse events such as CasA and "normal" Type II's also produced about $0.07 M_{\odot}$ of iron.

CONCLUSIONS

- (1) The integrated Type I (thermonuclear event) rate by number is ~10 percent of the corresponding rate of Type II (collapse) events.
- (2) The observed Type I thermonuclear rate today is ~10 percent of the average collapse event rate. This implies that the Type I rate can at best have remained constant in time over the course of galactic history, and might even have been lower in the past.
- (3) From SN 1987A light curve characteristics, we can now identify collapse events with the production of approximately $0.1 M_{\odot}$ of ^{56}Ni . Independent of surface "weather conditions" (whether red or blue), the luminosity should reach values within one

magnitude of the values characteristic of Type II supernovae at maximum optical light. (Typical Type II's have $M_V \sim -16.5$, SN 1987a peaked at $M_V \sim -15.5$.)

- 4) We emphasize the importance of a survey aimed at the establishment of the rate of 1987A-like events in our Galaxy and other galaxies. It is this rate (generalized Type II rate) that is relevant for neutrino searches.
We also emphasize the need for a survey of Type II light curves to determine whether a yield of ^{56}Ni of the order of $0.7 M_\odot$ is statistically accurate for "normal" Type II's.
- (5) We predict that the rate of Type I events in galaxies at increasing redshift should not increase, but rather remain constant or perhaps even decrease.
- (6) The origin of about half (or more) of the iron in the disk of the galaxy lies in collapse events (Type II supernovae) and thus iron tracks massive star deaths.
- (7) Metal abundance anomalies in extreme Population II objects might be attributed to massive star collapse events alone, since the O/Fe ratio in the ejecta is expected to vary with initial stellar mass. The contribution from massive stars $\geq 30 M_\odot$ are characterized by O/Fe ratios several times solar, while stars of mass $M \approx 20 M_\odot$ yield approximately solar O/Fe (SN 1987A).
- (8) The presence or absence of ^{56}Ni (^{56}Co), as indicated by the light curves, provides a potential probe of the correctness of

our arguments.

- (9) The ratio of the required integrated rate of nucleosynthesis events to the present rate of collapse events also holds important implications for galactic evolution.

Nucleochrometer arguments imply constancy to factor of ~ 2 accuracy.

ACKNOWLEDGEMENTS

The authors acknowledge the hospitality of the Aspen Center for Physics where this work was initiated and finalized. This work was supported in part by the NSF at the University of Chicago and at the University of Illinois and by the NASA/Fermilab astrophysics program.

REFERENCES

- W. D. Arnett 1988 - University of Chicago preprint.
- W. D. Arnett & D. N. Schramm 1973 - ApJ, 185 L47.
- B. Meyer and D. N. Schramm 1986 - ApJ, 311, 406
- B. M. Tinsley 1976 - ApJ. 108, 797.
- F. Theilemann and W. D. Arnett 1985 in Nucleosynthesis, ed. N. D. Arnett and J. Truran, Univ. of Chicago Press
- V. Trimble 1988 - Proc. Yanada Conference, Tokyo.
- S. Vandenberg, R. McClure and R. Evans 1987 - ApJ, 323, 44.
- S. Woosley 1988 - University of California, Santa Cruz preprint.
- S. Woosley and T. Weaver 1982 in Essays in Nuclear Astrophysics, ed. C. Barnes, D. Clayton and D. N. Schramm, Cambridge Univ. Press